On the origin of solar wind. Alfvén waves induced jump of coronal temperature

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Absorbtion of Alfvén waves is considered as the main mechanism of heating of solar corona. It is concluded that the sharp increase of the plasma temperature by two orders of magnitude is related to a self-induced opacity with respect to Alfvén waves. The maximal frequency for propagation of Alfvén waves is determined by the strongly temperature dependent kinematic viscosity. In such a way the temperature jump is due to absorption of high frequency Alfvén waves in a narrow layer above the solar surface. There is calculated the dissipated in this layer power, which blows up the plasma and gives birth to the solar wind. A model short wave-length (WKB) evaluation takes into account the $1/f^2$ frequency dependance of the transversal magnetic field and velocity spectral densities. Such spectral densities agree with an old magnetometer's data taken by Voyager 1 and recent theoretical calculations in the framework of Langevin-Burgers MHD. The present theory predicts existence of intensive high frequency Alfvén waves in the cold layer beneath the corona. It is shortly discussed how this statement can be checked experimentally. It is demonstrated that the magnitude of the Alfvén waves generating random noise and the solar wind velocity can be expressed only in terms of satellite experimental data.

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I. INTRODUCTION

Coronal heating mechanism is one of the most perplexing longstanding unresolved problems[1] of the contemporary physics in general. This is the reason why even some condensed matter theorists are involved in revealing of this mystery. The lack of complete experimental data prevents the advantages of a certain theoretical model from being clearly distinguished. In such a situation it is possible to apply purely aesthetic criteria for a natural description of some well-known facts. Such a fact is that the two orders of magnitude increase of the plasma temperature in the transition region is very sharp[2] – there is a smeared jump, which stands as a starting point for creation of solar wind. We wish to emphasize that complete magneto-hydrodynamics (MHD) simulations of Alfvén waves generated by a random driver also gives a sudden increase of the temperature as a function of height.[3] The purpose of the current work is to give a qualitative explanation of the observed temperature jump and to perform a model evaluation of its order of magnitude. Finally, we will analyze some possible future experimental observations described by the presented theoretical scenario. For example, the model predicts existence of intensive high frequency Alfvén waves beneath the coronal temperature jump.

II. SCENARIO

In order to make a proper assessment for the magnetic field spectrum comparable with magnetometers' data we need to switch to a frequency-dependence and perform a time averaging of the Fourier transformed wave component $\mathbf{B}(t) \approx B_x\hat{x} + B_y\hat{y}$ perpendicular to the constant magnetic field $\mathbf{B}_0 = B_{0,z}\hat{z}$ along which z-axis is chosen

$$\mathbf{B}(t) = \sum_{\omega_n} \exp(-i\omega_n t)\mathbf{B}_{\omega_n}, \quad \omega_n = \frac{2\pi}{\Delta t}n, \tag{1}$$

$$\mathbf{B}_{\omega_n} = \frac{1}{\Delta t}\int_0^{\Delta t} \exp(i\omega_n t)\mathbf{B}(t)\,\mathrm{d}t, \quad n = 0, \pm 1, \pm 2, \dots$$

As our purpose is to present a model evaluation, from now on we will consider only one of the fluctuating wave components, so that the plane magnetic field indexes will be further omitted. Fourier analysis of the signal accumulated for a time interval Δt gives us the opportunity to observe the magnetic field spectral density $\Phi(t)$, which is tightly bound to the time averaged square of the wave magnetic component

$$\langle B^2(t)\rangle = \frac{1}{\Delta t}\int_0^{\Delta t} B^2(t)\,\mathrm{d}t = \sum_{\omega_n} |B_{\omega_n}|^2 = \int \Phi(f)\,\mathrm{d}f. \tag{2}$$

The so-defined spectral density

$$\Phi(f) = \frac{1}{f_2 - f_1}\sum_{\omega_n} |B_{\omega_n}|^2, \quad \omega_n \in (\omega_1, \omega_2),$$
$$f = \omega/2\pi, \quad (f_2 - f_1)\Delta t \gg 1 \tag{3}$$

determines the magnetic field energy density w and the Alfvén waves energy flux S as a function of the circular ω or linear frequency f

$$w = \frac{B^2(t)}{2\mu_0}, \quad S = \frac{V_\mathrm{A}}{2\mu_0}\int \Phi(f)\,\mathrm{d}f. \tag{4}$$

In the interplanetary space the spectral density Φ is measured in typical units $\mathrm{nT}^2/\mathrm{Hz}$. The Alfvén waves energy density depends on the integrated spectral density and the Alfvén speed V_A. In general the integration should be taken over all possible wave frequencies $f \in (0,\infty)$ unless the given specific power spectrum imposes an introduction of a law or high frequency cut-off. In the suggested model we use the natural cut-off frequency set by the condition for waves existence $\omega_\mathrm{A}\tau_\mathrm{A}=1$, when the Alfvén waves frequency ω_A exactly equals the attenuation coefficient ${\tau_\mathrm{A}}^{-1}$. Therefore in our further investigation we should exclude the influence of some extremely high-frequency Alfvén waves that would be absorbed by the medium immediately after their generation under the solar surface and for heating in the corona should take into account only those, whose characteristic life time exceeds the inverse value of the cut-off frequency ω_c

$$\begin{aligned}\omega_\mathrm{A}\tau_\mathrm{A} &> 1, \quad \omega_\mathrm{A}=V_\mathrm{A}k_z, \quad 1/\tau_\mathrm{A}=\nu k^2,\\ \rho V_\mathrm{A}^2 &= B_{0,z}^2/\mu_0, \quad \omega_c=2\pi f_c = V_\mathrm{A}^2/\nu. \end{aligned} \tag{5}$$

The molecular kinetic theory[7] determines the temperature-dependence of the cut-off frequency, being a function of the kinematic viscosity ν. Since we pursue just a qualitative estimation, with a logarithmic accuracy in the final results for the solar wind velocity presented below, we can neglect the slight temperature changes in the protons' Coulomb logarithm L_p as well as the influence of the electron temperature dependence in the Debye radius a. Precise calculations including such a dependence would lead only to minor corrections that would not change the order of magnitude of the final outcome

$$\begin{aligned}\nu &= c_\nu T_p^{5/2}, \quad c_\nu=\frac{0.4}{M^{1/2}e^4 n_p L_p}, \quad L_p=\ln\frac{T_p a}{e^2}\gg 1,\\ \frac{1}{a^2} &= 4\pi e^2\left(\frac{n_e}{T_e}+\frac{n_p}{T_p}\right), \quad e^2\equiv\frac{q_e^2}{4\pi\varepsilon_0}. \end{aligned} \tag{6}$$

According to valuable analysis on the experimental data obtained by the Voyager 1 magnetometer[8], the magnetic field spectral density can be approximated by a single power law. Here we have taken into account that both magnetic and energy fluxes are almost constant along the magnetic field lines. In such a way the spectral parameter $\mathcal{D}$ on the solar surface can be evaluated by order of magnitude if we know the satellite spectral parameter $\mathcal{D}^{(\mathrm{sat})}$ and the ratio of the constant components of the magnetic field

$$\Phi(f)\approx\frac{\mathcal{D}}{f^2}, \quad \mathcal{D}\simeq\frac{B_{0,z}}{B_{0,z}^{(\mathrm{sat})}}\mathcal{D}^{(\mathrm{sat})}. \tag{7}$$

The observed power law for the energy density $\propto 1/f^2$ is theoretically explained in the framework of Langevin-Burgers MHD model[5]. The 1D calculations for the time and noise averaged spectral density of Alfvén waves generated by a white noise random driver for the external force density modeling the influence of the convective stochasticity

$$\langle F(t_1,z_1)F(t_2,z_2)\rangle=\tilde\Gamma\rho^2\delta(t_1-t_2)\delta(z_1-z_2) \tag{8}$$

reveal the same inverse proportionality to the second power of the Alfvén frequency

$$\overline{E}_f=\frac{\pi^2\rho V_\mathrm{A}^2\tilde\Gamma}{2\nu f^2 L}. \tag{9}$$

Comparison of the energy flux theoretically derived on the basis of Langevin-Burgers approach applied for modeling the role of the turbulence for generation of Alfvén waves with the experimentally observed energy flux could give us a reliable assessment for the Burgers parameter $\tilde\Gamma$

$$S=L\int V_\mathrm{A}\overline{E}_f\,\mathrm{d}f=\int\frac{\pi^2\rho V_\mathrm{A}^2\tilde\Gamma}{2\nu f^2}\,\mathrm{d}f=\int\frac{V_\mathrm{A}\mathcal{D}}{2\mu_0 f^2}\,\mathrm{d}f. \tag{10}$$

Thus, if we consider Burgers approach as adequate for a turbulence model description, we can extract information for the turbulence spectrum in the photosphere, at the footpoints of the magnetic field lines

$$\tilde\Gamma=\mathcal{D}\nu/\pi^2\mu_0\rho V_\mathrm{A}. \tag{11}$$

According to a recently proposed scenario[5,6] in the spirit of the old ideas for wave heating[10,13] Alfvén waves serve as mediators, carriers of energy from the turbulent photosphere to the hot solar atmosphere, where in a small region the high-frequency waves intensively attenuate and heat the corona. In this work we present a model evaluation for the absorbed in the transition zone energy flux, whose strong temperature dependence is determined by temperature dependence of the cut-off frequency f_c and naturally results in a sharp temperature jump[6]

$$f_c=\frac{V_\mathrm{A}^2}{2\pi c_\nu T^{5/2}}. \tag{12}$$

The absorbed energy flux is taken from magnetometric data analysis, but it may also be obtained by a thermodynamical approach. If the comparatively small effects associated with radiative losses and compression are neglected the absorption rate will be related only to the plasma internal energy density ε and the conducted work

$$\begin{aligned}S_\mathrm{Abs} &= V_\mathrm{A}\int_{f_c}^{\infty}\frac{\mathcal{D}}{2\mu_0 f^2}\,\mathrm{d}f=\frac{V_\mathrm{A}\mathcal{D}}{2\mu_0 f_c}=\frac{\pi c_\nu\mathcal{D}}{\mu_0 V_\mathrm{A}}T_p^{5/2}\\ &\approx \varepsilon v+pv, \quad \varepsilon=\frac{3}{2}p, \quad p=n_eT_e+n_pT_p, \end{aligned} \tag{13}$$

where p and v are respectively the plasma pressure and velocity. In such a way we can derive the approximate rate for the velocity of the solar wind, driven by sharp coronal temperature increase due to absorption of intensive high frequency Alfvén waves, for which the transition region plasma is opaque

$$v_\mathrm{wind}\simeq\frac{0.08\,\pi\mathcal{D}T_p^{3/2}}{\mu_0 V_\mathrm{A} M^{1/2}e^4 n_p^2 L_p}, \quad T_p\sim T_e. \tag{14}$$

As the shear viscous friction heats[11] the heavy particles, the proton temperature T_p is significantly higher than electron one T_e, however, for an order of magnitude evaluation here we suppose the electron temperature T_e to be similar to the proton one T_p.

III. DISCUSSION AND CONCLUSIONS

With a logarithmic accuracy we have derived an explicit formula for the initial velocity of the solar wind. This formula Eq. (14) is completely based on experimentally accessible parameters and can be easily rejected if it gives more than 3 orders of magnitude difference. But, if this model remains on the arena, let us shortly discuss what has to be done as a future perspective in order to finally solve the perplexing longstanding mystery for the origin of coronal heating and solar wind. First of all, numerical simulations on MHD with white noise random driver[3] (Langevin-Burgers MHD) has to be repeated to reproduce a δ-like maximum of the energy dissipation density at the transition region.

Here we wish to insert a short historical remark. The stochastic mechanics in general was introduced by Langevin[16] 1905 to explain the Brownian motion. Later on Burgers 1948 introduces the white noise random driver in the hydrodynamics of turbulence. Much later, in 1995, Polyakov[15] derived Kolmogorov power laws[9] using Langevin-Burgers approach, but his research remained unobserved in astrophysics, not speaking about heliophysicists. That is why using random generator in MHD simulations is simply called random driver, but almost never the magnitude of the noise is evaluated by real experimental data.

In the recent work we have only evaluated the area under the sharp maximum of dissipation and now it is time to perform a state of the art calculations with a realistic random force with a spectral density corresponding to the data taken by the satellites' magnetometers. For example, the turbulence spectrum can be treated with the assessment, based on the Langevin-Burgers model Eq. (11). We advocate that the physical mechanism for the origin of solar wind and coronal heating is already revealed and it is only a matter of honest numerical work to create a coherent picture. The results for the temperature jump and dissipation maximum has to be compared with the observations and other theoretical scenarios like magnetic reconnections[4], for example. Each model unable to reproduce a sharp temperature increase in height has to be reconsidered for the waist basket. The same can be said for the models based on Ohmic heating which predict electron temperature higher than the proton one. Though the latter statement seems to be true for the X-ray bright points, it is definitely not valid for the corona as a whole.

Second, in order to evaluate the properties of solar surface as a random driver all the old data from Voyager 1 has to be meticulously analyzed and a detailed investigation by the forthcoming Solar Orbiter mission has to be planned.

Third, the Sun is a unique system for investigation of convective turbulence. It will be very interesting to compare the satellites' data for the magnetic field spectral density with results based on theoretical modeling of turbulence. The maturity of solar physics can stimulate significant development of the achievements in the contemporary turbulence research. For instance, $1/f^2$ power law by Burlaga and Mish[8] corresponds to one-dimensional $(k_x, k_y = 0)$ propagation of Alfvén waves in the framework of Langevin MHD[5], as the whole noise is created by the random motion of the funnel foot-points.

Lastly, now we operate with a realistic 3D model for the distribution of magnetic field from the solar surface to the satellite. The perturbation of magnetic field lines serve as a string of a harp to deliver the information about the solar turbulence from the photosphere to the magnetometer. Owing to propagation of Alfvén waves we can "listen" to the sounds of the great solar symphony. Due to absorption of the high frequency modes, however, at the transition region where the temperature jumps occur we are able to hear only the basses, whereas for the ultraviolet band we remain absolutely deaf. As a current problem which deserves to be put on the agenda is to observe the powerful high frequency Alfvén modes *under* the corona[12]. A kamikaze satellite could give some information, but for systematic research we need to learn how to extract the behavior of the solar surface as a random driver using optical data. Only after a proper incorporation of these ingredients we can conclude that our understanding of heating mechanism is complete.

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